Renewable and Sustainable Energy Reviews 22 (2013) 515–526

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Testing, inspecting and monitoring technologies for wind turbine blades: A survey

Bin Yang*, Dongbai Sun

National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 28 December 2010
Received in revised form
25 December 2012
Accepted 26 December 2012
Available online 15 March 2013

Keywords:
Wind turbine blades
Testing
Inspecting
Monitoring
Service safety

ABSTRACT

Renewable wind energy is one of the most efficient and effective ways to deal with global warming and energy crisis. Recently, wind energy has grown at an impressive rate in entire world. As we know, the blades are the most important components of wind turbine. In order to increase the energy conversion efficiency, the size of wind turbine blades becomes more and more big which blade diameter ranges from about 20 m to about 100 m or even. However, wind turbine blades are facing increasingly harsh and complexity service environment. It is necessary to testing, inspecting and monitoring of wind turbine blades in order to guarantee the service safety of wind turbine blades. This paper surveys the testing, inspecting and monitoring technologies for wind turbine blades, including mechanical property testing, non-destructive testing/inspecting, full-scale testing, structural health monitoring and condition monitoring. And then, the development trends and some suggestions of testing, inspecting and monitoring technologies for wind turbine blades are discussed.

Contents

1. Introduction

With the increasing negative effects of fossil energy on the environment, such as global warming and crisis of energy availability, have forced many countries to develop environmentally friendly alternatives including solar, wind and solar-hydrogen energies that are renewable to sustain the increasing energy demand. Wind energy, the world's fastest growing energy source, is a clean and renewable source of energy. Now more and more countries had paid more attention to wind energy especially in Europe, the United States and more recently in China and other nations [1,2].

Most wind turbines, both large and small, have the same basic parts: blades, shafts, gears, generator, and a cable (some turbines do not have gearboxes). These components work together to convert the wind energy into electricity. As we know wind turbines capture the

* Corresponding author. Tel.: +86 138 1096 9390; fax: +86 10 6233 2239.
E-mail address: ustbyangbin@yahoo.cn (B. Yang).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.12.056

most energy depended on their propeller-like blades. So, the blades are the most important critical parts of wind turbine. And the manufacturing cost of wind turbine blade is about 15–20% of wind turbine production cost. In order to increase the energy conversion efficiency, the size of wind turbine blades becomes more and more large which blade diameter ranges from about 20 m to about 100 m or even [3]. However, gradually bigger blades are facing harsh and complexity service environment which have brought an amount of service safety problems. The blades can be damaged by moisture absorption, sleet, ultraviolet irradiation, atmospheric corrosion, fatigue, wind gusts or lightening strikes and so on. Furthermore, wind turbine blade failure is very costly because it can damage other blades, the wind turbine itself, and other wind turbines located in neighbor [4]. So, it is important to detect the damage before the blade fails catastrophically which could destroy the entire wind turbine. The efficient testing, inspecting and monitoring procedures should extend wind turbine life and reduce failure possibility. Furthermore, it is also necessary to perform continuous structural health monitoring of wind turbine blades, in order to estimate level of critical damage at an initial stage before collapsing and to perform detailed inspecting and testing with elimination of the broken-down components.

To keep the wind turbine blades in continuous operation, testing, inspecting, and monitoring technologies of the wind turbines blades, including mechanical property testing, non-destructive testing/inspecting, structural health monitoring, full-scale testing and so on, become more and more important for reliability of wind turbine system and are widely applied to guarantee the service safety of wind turbine blades.

The main object of this paper is to provide a survey of the current testing, inspecting and monitoring techniques for wind turbines blades, based on published evidence. This paper is organized as following. In Section 2, current states of wind turbine blades are be depicted, in Section 3, we discussed the mechanical property testing technologies of wind turbine blades, in Section 4, full-scale testing technologies have also been introduced, non-destructive testing technologies are be reviewed and discussed. Structural health monitoring and condition monitoring for wind turbine blades follow in Section 6. Section 7 presents the new trend of testing, inspecting, and monitoring technologies of wind turbine blades. And finally, the Section 8 is our conclusions.

2. Current states of wind turbine blades

The high demand for green energy is causing a rapid increase in renewable energy. In this regard, the utilization of renewable energy resources, such as solar, geothermal, and wind energy, appears to be one of the most efficient and effective ways in dealing with environment pollution and energy crisis. Recently, wind power as the most promising and mature renewable energy has grown at an impressive rate in the entire world. Birger T. Madsen, from BTM Consult ApS (Rinkøbing, Denmark), forecasted that cumulative installed capacity will reach nearly 1,000 GW by 2020. That capacity, he contended, will enable wind power to provide 7–8% of the world's electricity demand by 2020 [4].

Wind turbines are machines that turn wind energy into mechanical energy, which is then used to produce electricity. Generally, wind turbine includes three blades. This configuration is more efficient because it can spin the rotor at higher speeds in lower wind. Three blade designs are also easier to balance. Wind turbine blades are very similar in function to glider wings. Both are designed for maximum lift and efficiency with minimum drag. So, the ability of energy capture of wind turbine system can be decided by blades. And, it included two key issues: structure and materials.

On the one hand, the structure of wind turbine blades has the characteristics of curved surface, multi-layered, variable thickness and big size. And the blades size is one of the most important problems of structure design in wind turbine blades. In order to obtain a greater efficiency of energy capture, within the past few years there has been a dramatic increase in the size and power output of wind turbines, from a rated power of 50 kW in the late 1970s to the multi-megawatt power plants of today. The world's largest wind turbine is now the Enercon (E-126). This turbine has a rotor diameter of 126 m (413 feet), formerly rated at 7 MW [5]. The big change of rotor diameter can be displayed in Fig. 1. It is anticipated that wind turbines with a rated power output in the range of 8–10 MW and a rotor diameter from 180–200 m will be developed and installed within the next 10–15 years [6]. However, an increase in rotor diameter is accompanied by a corresponding increase in the load levels experienced by the blades, input shaft, gearbox and generator, as well as by the tower and nacelle. It can significantly affect the service safety of wind turbine blades.

On the other hand, blades materials significantly affect the performance and properties of blades, such as blade weight, damage mechanism, and fatigue life and so on. Wind turbine blades are made from anisotropic materials, which are usually made in polymer matrix composites materials, in a combination of monolithic (single skin) and sandwich composites [7]. Present day designs are mainly based on glass fiber-reinforced composites (GFRP), but for very large blades carbon fiber-reinforced composites are being used increasingly to reduce the weight. The sandwich structures can be considered as a special type of composite laminate and have gained widespread acceptance as an excellent way to obtain extremely lightweight components and structures with very high bending stiffness, high strength, and high buckling resistance. These materials were processed by

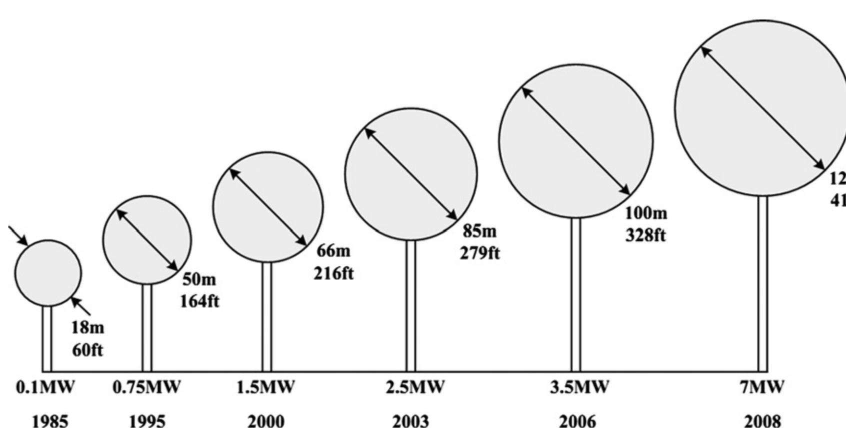

Fig. 1. The change of wind turbine blades.

resin transfer molding (RTM), vacuum assisted RTM (VARTM), SCRIMPTM infusion and so on [8]. Generally, wind blade materials must withstand severe fatigue loading under service environments. Various materials and versus process have significantly affected the service life under complexity loads.

Therefore, to extend the lifecycle of wind turbine blades and minimize the operation risks, it is necessary to look for effective testing, inspecting and monitoring technologies according to the characteristics of structure and materials of wind turbine blades. The owners, operators, investors, manufacturers can also benefit from these technologies.

3. Mechanical property testing

Mechanical property testing is usually carried out on coupons and subcomponents with a representative lay-up and a processing route similar to that of the blade in question. Mechanical properties are measured under tensile, compressive and shear loads, or combinations thereof, which major include static testing, fatigue testing and modal testing. The purpose of static testing is to verify the capacity of sustaining limit load. Generally, the sufficient safety load will be applied in predetermined direction, which can be used to test its buckling stability. Fatigue testing is carried out under cyclic loading, normally with constant amplitude. The fundamental purpose of performing fatigue testing on wind turbine blades is to demonstrate that a blade has the prescribed reliability and service life. Model testing is a process of determining the modal parameters for a construction and it is the common used method to characterize the dynamic properties of a mechanical system.

3.1. Static testing

Generally, the wind turbine blades should be sufficiently stiff in order not to collide with the tower during operational loading. Blade deflection and strains are measured at predetermined locations. In static testing, loads are applied to the blade statically in one direction to establish its ultimate strength. This static testing can either be intentionally destructive or non-destructive. Static testing is done with the purpose of predicting a blade's ability to withstand extreme loads such as those caused by hurricane wind forces or unusual transient conditions, in order to determine the ultimate strength of the blade. Most of static testing includes the pressure and gravity load on the blade results in edgewise and flapwise bending, as well as torsional loading of the blade [9].

Many famous institutions and universities pay more attention to the static testing of wind turbine blades. In [10], static testing of the composite wind turbine blade were carried out by using the embedded fiber Bragg grating (FBG) sensors for the structural performance tests. The down scaled composite wind turbine blades, the 1/23 scale of the 750 kW composite blade, was used for the structural performance tests to predict the structural behavior and also to verify the capability of FBG sensors. In static testing, the deflections along the blade were predicted with simple beam theory and quadratic fitting method by using the embedded FBG sensors.

In [11], structural investigation of composite wind turbine blade considering structural collapse in full-scale static tests is carried out. A 40 m full-scale wind turbine blade made of E-glass/epoxy for a class horizontal axis wind turbine system was tested to failure under flap-wise loading.

In 2000, the National Renewable Energy Laboratory (NREL) has finished the comprehensive testing of Nedwind 12-m wind turbine blades [12]. In this testing, the total of 36 strain measurements and two bending bridges were used for each blade. This project measures the blade displacements at the load application point and at the tip for each blade test. And, the flap load and edge load were used to testing the blades. Static load tests were performed at 110% of the extreme design load for strain verification. The static testing results have showed that no structural failure or buckling stability limits were reached.

The National Wind Technology Center of Sandia National Laboratories has researched the static structural testing of 9 m carbon fiber wind turbine blades in 2007 [13]. The blades were mounted to some different test stand and subjected to a flapwise bending load case to approximate the extreme loading events for the wind class that each blade was designed to. All blades were loaded by use of a three-point whiffle-tree and saddle arrangement connected to an overhead bridge crane. And, an array of sensors was used in the tests to monitor strain, deflection, load, and acoustic emissions. Acoustic microphones were able to detect areas where damage was occurring, and indicated the beginnings of failure.

Risø National Laboratory has also researched static testing of cross-section of wind turbine blade [14]. In this paper, a 250 kN Instron material machine is used to control the displacement. In [15], a 34-m composite wind turbine blade manufactured by SSP-Technology A/S has been tested in flapwise bending until collapse. In this project, ovalization of the load carrying box girder results a non-linear loading, and non-linear finite element (FE) analyses at different scales were employed to calibrate test measurements. Comparisons between measurements and FE-simulations showed that delamination of the outer skin was the initial failure mechanism followed by delamination buckling which then led to collapse. When the skin debond reaches a certain size the buckling strength of the load carrying laminate becomes critical and final collapse occurred.

In [16], an experimental investigation has been done on a blade section in order to measure the flapwise and edgewise bending stiffness and torsional stiffness as well as the bend-twist coupling. These tests have been successfully compared with numeric finite element models, when the blade has been loaded in the linear elastic domain and compared with global displacements.

In [17], the presented work has primarily been concerned with a comprehensive analysis of the findings of the static flapwise experimental test to collapse of a generic wind turbine blade, as well as the correlation of the experimental evidence with the predictions of equivalent single-layer finite element models. In [18], this paper reports the results of over 250 static and fatigue tests of specimens. The static testing includes four specimen geometries and two static testing rates. The 140 static testing results indicate that the average strengths are similar for two no reinforcement geometries, while two corresponding reinforced geometries are significantly stronger, with lower coefficients of variation. And the experiment result shows static strengths were insensitive to differences in test rate.

In additional, fewer corporations have development static testing machines to help researchers launch and maintain a successful wind turbine blade static test program. Such as MTS [19], leveraging proven technology for subjecting wings and other large aerospace components to massive loads, their solutions combine robust hydraulic winch and/or linear actuation technologies to achieve coordinated, precision loading and closed-loop control at multiple pull points along the blade.

Different static testing has been performed under different load ways. On the one hand, the most common of these uses electric winch system, due to ease of controlling it. Hydraulic actuators have also been used in the past but large displacements in longer blades make them an expensive option. On the other hand, some subcomponents, other parts of wind turbine blades, and full/large-scale wind turbine blades also were applied to static testing. The generally static testing is shown in Fig. 2. Obviously, static testing still plays an important role in evaluating the performance of wind turbine blades.

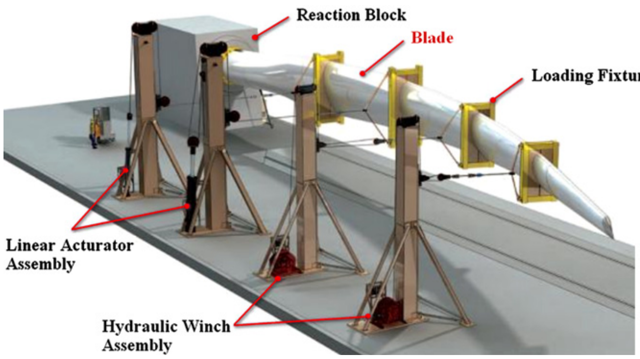

Fig. 2. Wind turbine blade static testing [19].

3.2. Fatigue testing

Generally speaking, the objectives of this fatigue test were to: (1) determine structural properties of the blade through fatigue testing; (2) determine fatigue strength and failure mode of the blade; and (3) investigate new sensor technologies for damage detection and structural health monitoring. Fatigue tests apply a loading spectrum which may contain a 1 million to 5 million load cycles. It is typically performed in two primary directions, flap and lead-lag. Blades can be fatigue tested sequentially, first in the edgewise direction followed by testing in the flapwise direction [20].

There are many laboratories throughout the world have researched fatigue testing of the wind turbine blades using different facility which developed by themselves, such as RISØ National Laboratories in Denmark, National Renewable energy Laboratories (NREL) in US. In [21], a new method for dual-axis fatigue testing has been developed in which the flapwise and edgewise directions are tested simultaneously, thus also allowing the interactions between the two mutually perpendicular loads to be investigated. However, the traditional fatigue testing is usually performed about the flapwise and edgewise axes independently. The research result is shown the dual-axis approach is also a much quicker test method. If use the dual-axis fatigue testing approach, the required testing time is reduced to only 60% of the time that is required to perform the equivalent sequential single-axis tests. The results show that dual-axis testing is more representative of the loading seen in service and can thus contribute to optimization of the blade mass and structural performance.

In [22], a small blade fatigue test system was be developed successfully, which met the criterion of the IEC (TR 61400-23) for the small composite wind turbine blades (SCWTBs). The fatigue test system was able to test 1 m–3 m SCWTBs with single or multiple samples tested simultaneously. The fatigue test machine consisted of the servo motor, linear guide, transmission, controlling system and clamping apparatuses. Amplitude of fatigue can be manipulated by rotating the eccentric holes of the flywheel. Because vibration frequency of the fatigue test system was limited to 3–6 Hz, this research also tested the repaired samples after breaking them intentionally for the tests.

In [23,24], the National Renewable Energy Laboratory's (NREL) National Wind Technology Center (NWTC) had carried out the full-scale fatigue tests of two 9-m CX-100 wind turbine blades. Different type sensors are used to monitor the blades, such as piezoelectric transducers, accelerometers, acoustic emission, and foil strain gauges. The blades underwent harmonic excitation at their first natural frequency using the Universal Resonant Excitation (UREX) system at NREL. Blades were initially excited at 25% of their design load, and then with steadily increasing loads until each blade reached failure. The data were analyzed to identify fatigue damage initiation and to assess damage progression.

In [25], two fiberglass reinforced composites blades were fatigue tested on a full scale blade testing facility. Acoustic Emission(AE) was used to evaluate blade damage developed through a fatigue process from dynamic loading. AE signature analysis focused on counting, amplitude distribution and location. This gives non-destructive evaluation assessment of damage status, failure modes and failure location. Blade mechanical properties such as natural frequency, elastic modulus and tip deflection were measured during the fatigue testing. The change of mechanical properties indicates degradation of blade structured integrity. The correlation between AE evaluation and blade damage was obtained by comparing AE signatures and the blade mechanical properties, which changed during the testing.

In [26], a 9 m TX-100 wind turbine blade was recently fatigue tested to blade failure at the NREL. At a fatigue cycle rate around 1.2 Hz, and after more than 4,000,000 fatigue cycles, the blade was diagnostically and visibly failing at the blade spar cap termination point at 4.5 m. For safety reasons, the testing was stopped just before the blade completely failed. A commercial off-the-shelf Physical Acoustics Corporation acoustic emission system gathered blade AE data throughout the test.

NREL developed a dual-axis fatigue test system in 1999 [27]. This system uses constant amplitude displacements to apply the damage cycles. Compared with single-axis test system, several practical challenges of dual-axis fatigue testing system have been implemented, as hardware complexity increased dramatically with two actuators applying the loads at right angles to each other. A custom bellcrank was designed and implemented to minimize the load angle errors and to prevent actuator side loading. The control system was upgraded to accept load and displacement feedback from two actuators. The inherent long strokes uniquely associated with wind turbine blade-tests required substantial real-time corrections for both the control and data systems. A custom data acquisition and control system were developed using a National Instruments LabVIEW platform that interfaces with proprietary servo-hydraulic software developed by MTS Corporation. The implementation of two-axis testing at NREL has enabled more realistic fatigue blade testing to be conducted.

In 2005, NREL developed a new hybrid fatigue testing system called the Blade Resonance Excitation (B-REX) test system[28]. The new system uses 65% less energy to test large wind turbine blades in half the time of NREL's dual-axis forced-displacement test method with lower equipment and operating costs. The B-REX is a dual-axis test system that combines resonance excitation with forced hydraulic loading to reduce the total test time required while representing the operating strains on the critical inboard blade stations more accurately than a single-axis test system. The B-REX test system was evaluated under stable operating conditions using a combination of various sensors. The evaluation results were compared with results from the same blade, tested previously using NREL's dual-axis forced-displacement test method. Experimental results indicate that strain levels produced by the B-REX system accurately replicated the forced-displacement method.

In [29], NREL uses resonance excitation in the flap direction to reduce the cost and time required to perform a full-life fatigue test. By using hydraulic actuators instead of an eccentric mass to excite the blade in the flap direction, the system will be able to regulate the blade flap displacement independently of the excitation frequency. The new test method is the first time to combine resonance excitation and dual-axis fatigue testing. After an in-depth analysis of blade loads, a progressive time history of the phase angle between the flap and lead-lag displacements has been developed that will provide more realistic testing conditions than the current constant phase angle.

In addition, some researchers have focused on the accelerated fatigue testing. There are currently two methods used for the accelerated fatigue testing of large wind turbine blades: through the use of eccentric rotating mass (shaker) to vibrate the blade close to its natural frequency of vibration and using hydraulic actuators to flex the blade. Of the two methods flexing the blade using hydraulic actuators will simulate the fatigue loading more realistically. And, both the shaker and hydraulic actuator systems are applicable for the testing of small wind turbine blades. Hydraulic actuators, however, are more suited to large blade testing as the flexing forces are high and the flexing frequency low. In [30], a 2.5 m long glass fiber reinforced plastic composite wind turbine blade was fatigue tested by means of a mechanically operated test rig. The rig uses a crank eccentric mechanism to flex the blade by a constant displacement in the flapwise direction for each load cycle. A crack started in a region of the blade where the highest stresses were predicted by the detailed finite element model of the blade.

In [18], the authors have also researched fatigue testing of thick adhesive joints for wind turbine blades. Fatigue loading conditions include both tension and reversed loading. The four geometries are compared as to static strength statistics and fatigue lifetime trends. Tensile fatigue results show relatively low fatigue sensitivity in terms of fatigue exponent, for no reinforcement geometries. Additional reinforcement geometries showed somewhat greater sensitivity in terms of fatigue exponent, but fatigue strengths at 10^6 cycles were significantly higher than for the unreinforced geometries. Reversed tension–compression loading produced a shift in failure mode to interlaminar in the adherend.

In [31], a fatigue test of a wind turbine blade was conducted by acoustic emission at the NREL, starting with the second loading level. The acoustic emission data showed that this load exceeded the strength of the blade. This experiment shows that fatigue tests of large fiberglass reinforced plastic (FRP) wind turbine blades can be monitored by acoustic emission techniques. The system showed that the peak load was too high so that it could have been decreased before significant damage was done to the blade. The blade data indicated that the increase in the load exceeded the low cycle fatigue strength of the blade.

As blades have become larger, heavier, and more expensive, the importance of fatigue testing has also increased. At the same time, test methods that were developed for smaller blades have become more expensive and less effective. More and more fatigue testing methods require complexity loads was exerted on full scale blades to validate the performance for wind turbine blades. Obviously, dual-axis testing can in principle, better simulate loads experienced in the field and can result in shorter overall test duration. In the future, a new method was required to be developed to test the blades, keeping the costs down and to allow more complexity fatigue testing.

3.3. Modal testing

As a part of the certification procedure for wind turbine blades, it is recommended to determine the natural frequencies and damping of the blade. In the recent years, wind turbine blades are getting larger and relatively more flexible than earlier. This has caused increasing attention to instability problems due to this matter. In connection with development of new wind turbine blades in the future there is a need for verification of the structural properties (mass – stiffness – and damping) in a better way than it is possible today. That will give one the possibility to adjust these properties already on the proto type stage. By this it is possible to reduce the probability for instability of the blade.

Modal testing analysis is a process of determining the modal parameters for a construction and it is the common used method to characterize the dynamic properties of a mechanical system. It can be accomplished through experimental techniques and produces interpretable results. Modal testing of wind turbine blades has been used to determine the natural frequencies, damping and the mode shapes.

In [32], an experimentally updated wind turbine model was researched that accurately reflected the operational dynamics of the CX-100 Micon 65/13 wind turbine in order to operational monitoring system development. Experiments were performed to acquire the modal frequencies, damping ratios, and mode shapes of the CX-100 sensored rotor blade in free boundary conditions and of the same rotor blade mounted to the wind turbine with two other unsensored rotor blades.

In [33], modal testing was used to obtain a thorough dynamic characterization of a CX-100 wind turbine blade. And then the results of this dynamic characterization were used to validate a numerical model and understudied the effect of structural damage on the performance of the blades. Also, structural health monitoring (SHM) techniques was employed on the blade surface to detect changes in the blade dynamic properties. SHM design parameters such as traveling distance of the wave were examined. Results obtained during modal and SHM testing will provide a baseline for future work in blade damage detection and mitigation.

In [34], an experimental modal model was developed to relate the forces introduced by wind loads to the response of the structure. Additionally, operational modal analysis was conducted in an indoor simulated wind environment test bed. A modal filtering technique was applied and verified using an electrodynamic shaker and was then used to analyze the operational data. The effects of wind speed and shear on the modal response were investigated. The key results were a shift down in resonance frequencies with increasing height of the turbine tower for rotor modes coupled to the tower response and significant changes in operational modal response for non-uniform (sheared) wind conditions, especially from the 5 Hz mode of vibration.

In [35], the model analysis is done on a blade of length 38.95 m which is designed for V82-1.65 MW horizontal axis wind turbine (supplied by Vestas). The airfoil taken for the blade is NACA 634-221 which is same from root to tip. In the work, five shapes of spar are used for the model analysis. The ansys 12.0 is used for the finite element analysis. The satisfactory results had been obtained. Therefore, the research results can be used for vibration analysis of turbo machinery blades and helicopter rotor blades.

In [36], the wind turbine blade is represented by some simplified shapes. And the modal analysis techniques applied in experiments using a uniform and a stepped beam. Four different methods are used for obtaining the natural frequencies, and flapwise, edge-wise and torsional natural frequencies are calculated. The results showed that some discrepancies between measured frequencies results and the computed frequencies can be observed for highest frequencies. This means that an effective method to compute natural frequencies of a simplified wind turbine blade was feasible.

In [37], the structural modal analysis of full-scale 48 m fiberglass composite wind turbine blades for 5 MW horizontal axis wind turbine was investigated, and through this to assess the potential for materials savings and consequent reductions of the rotor weight. Five types of spars cross-section are taken in this work, and the finite element modal analysis of designed blade is done in ABAQUS. A numerical work has been used to address the most adequate spar shape and to get an understanding of the complex structural behavior of wind turbine blades. Five different types of structural reinforcements helping to prevent undesired

structural elastic mechanisms are presented. Comparisons of the eigenfrequencies observed in the full-scale tests are presented.

In [38], a customized Pontos point tracking photogrammetry system was used for dynamic field measurements on a 500 kW Nordtank wind turbine at the Risoe DTU campus in Denmark. Data was acquired at 100 Hz for 7 s from more than 50 targets within a 50 m wide field of view. Results include movies with animated vectors and associated time history plots for 3D directional and resultant displacements of all blades and the support tower, as well as trajectory plots.

In [39], operational modal analysis (OMA) was used for experimental modal analysis of wind turbine blades which allows extracting modal parameters based on measuring only the responses of a structure under ambient or operational excitation which is not needed to be measured. The study shows that the aeroelastic phenomena due to rotor rotation dramatically changes the character of aerodynamic excitation and sets limitations on the applicability of OMA to operational wind turbines.

In [40], a modal re-analysis approach is proposed for refinement designs of rotary wind turbine blades on the basis of matrix perturbation methods. The approach entails effects of stress stiffening, spin softening, uncertainty of material properties and structural modifications of blades. Three perturbation methods are used to conduct the re-analysis approach, including the standard perturbation method and two improvements proposed, respectively. The numerical results indicate that the two improved methods deliver better accuracy than the standard perturbation method in terms of eigenpairs. In application to blade designs, one of the improved methods is suitable for a multi-step modal re-analysis with explicit small parameters and cultivates the first-order and second-order perturbations of eigenpairs as well. Another improved method is a better choice for a single-step modal re-analysis without determining any small parameter explicitly and directly offers approximate eigenpairs instead of somehow tedious perturbation processes.

In [41], some test results from a wind turbine blade with different induced cracks show that some of the modes of the blade are significantly affected by a crack and that the modal parameters change more significantly with a more severe crack. Obviously, any change in the physical properties of a structure should cause a change in its modal parameters.

In [42], structural studies of a medium scale composite wind turbine blade construction made of epoxy glass fiber for a 750 kW rated power stall regulated horizontal axis wind turbine system is presented. The complex geometry of the blade with a skin-spar foam sandwich structure was generated by utilizing commercial code ANSYS finite element package. Dimensions of twist, chord and thickness were developed by computer program. The focus is the natural frequencies and modal shapes of the rotor blade which was calculated for defining dynamic characteristics. And structural analysis was performed by finite element method in order to evaluate and confirm the blade to be sound and stable under various load conditions.

In [43], the results of in-field tests performed on a 2.5 MW, 80 m diameter wind turbine are presented. Three different measurement systems, namely conventional strain gauges, photogrammetry and laser interferometry, are used to monitor dynamic response of wind turbine blades during the two test campaigns. An operational modal analysis algorithm based on the least square complex exponential method is used to analyze the recorded data. Several turbine parameters (eigenfrequencies and damping ratios) were obtained.

In [44], Risø National Laboratory has researched modal analysis of wind turbine blades. At this project there were obtained good results doing modal analysis on a 19.1 m wind turbine blade. And the experimental analysis of the blade has been compared with results from a FE-modeling of the same blade. For some of the higher modes substantial discrepancies between the natural frequencies originating from the FE-modeling and the modal analysis, respectively, are observed. It was demonstrated that it was possible to determine the natural frequencies, damping and the mode shapes by use of modal analysis.

In [45], Risø National Laboratory has performed another modal analysis of wind turbine blades. The measurements have been performed on three different wind turbine blades. The length of the blades used during the experimental campaigns varies between 7.5 m and app. 35.0 m. And it is believed that the results also are valid for blades exceeding this size. In this project, different methods to measure the position and adjust the direction of the measuring points are discussed. Different equipment for mounting the accelerometers is investigated and the method using an angular steel plate was chosen. Different excitation techniques are tried during experimental campaigns. Some measurement errors have been eliminated by repeating measurements on the same wind turbine blade. Finally, the results obtained from modal analysis, carried out on a wind turbine blade are compared with results obtained from the Stig Øyes blade_EV1 program. Comparison between the results obtained with this two methods, shows a good correlation when comparing the frequency and mode shapes.

In [12], NREL has also conducted a modal testing. They can obtain the first and second flap and edge blade frequencies and the first torsional frequency, the damping for the first flap and edge modes. The torsional frequency was determined by measuring the cross product of the accelerations at the leading and trailing edge of the blade chord at 83% span. This damping measurement was made with the tip chord horizontal for the flap measurement, and vertical for the edge measurement. The critical damping coefficient was determined by fitting a damped sine wave to the data, using a nonlinear regression program NLREG [46].

In China, Fellow of Chinese Academy of Sciences Mao [47] has researched the modal testing and analysis of wind turbine blades. In this paper, a full scale wind turbine blade modal test has been carried out on the test bed constructed by Institute of thermal Physics of Chinese Academy of Science. The blade tested has a rated power of 1.5 MW and was 38 m length. The mode was tested desperately in flat wise and edge wise direction. Modal criterions such as Modal Assurance Criterion (MAC) and Mode Over Complexity(MOV) were then used to validate the results. Results show that the testing method adopted in this paper is suitable for modal testing of full scale turbine blades. And, FEA method was the then used to simulate blade mode, and vibration identity was got. The comparison between experiment and numerical simulation showed that the approximation before was reasonable, which significantly simplified the FEA model with acceptable sacrifice of precision. The time cost and hardware requirements of the simulation indicate FEA is a feasible method for blade design.

In conclusion, modal testing is playing an increasingly important role for not only new blade designs but also the blades reliability analysis. The structural integrity of blades is critical to the continued operation of a wind turbine. Resonant or modal properties of wind turbine blades are directly influenced by its physical properties. In the future, the complete wind turbine structural mechanical response at different load conditions is of particular interest. Different branches of experimental modal analysis is promising for big structures such as wind turbines, which allows extracting modal parameters based on measuring only the responses of a structure under ambient or operational excitation which is not needed to be measured.

4. Full scale testing

Both the composite material used and the overall structural behavior of the blade bring about significant uncertainty because of the load carrying capacity. In order to reduce these uncertainties, the wind turbine standards IEC 61400-1 [48] and IEC 61400-22 [49] require that tests with both the composite material and the full-scale blade are performed. Full-scale tests are conducted in order to verify the strength of the blades in both ultimate and fatigue limit state. The requirements to full-scale testing are given in IEC 61400-23 [50]. Full-scale tests normally contain the following subtests: (1) blade properties (weight, elastic properties, natural frequencies, etc.); (2) static strength (flapwise/edgewise); (3) fatigue strength (flapwise/edgewise); and(4) static strength after fatigue tests (flapwise/edgewise).

In 2012, the NREL had finished the full-scale testing of a 45-m wind turbine blade [51]. This project was a purely funds-in CRADA with Modular Wind Energy (MWE). NREL provided the capabilities, facilities, and equipment to test this large-scale MWE wind turbine blade. Full-scale testing has demonstrated the ability of the wind turbine blade to withstand static design load cases and demonstrate the fatigue durability. Through this CRADA, MWE would obtain test results necessary for product development and certification, and NREL would benefit by working with an industrial partner to better understand the unique test requirements for wind turbine blades with advanced structural designs.

In [52], a useful practical technique (the video-metric technique) for measuring the deformation of large-scale wind turbine blade in the full-scale tests is presented. The main advantages of the videometric are quick data capture in situ, adaptability to large-scale three-dimensional measurement and various environments. The application examples and the obtained data analysis have demonstrated the technique's application on large-scale wind turbine blade, and which is relevant to understanding the structural behavior of wind turbine blade in the full-scale tests and during operation.

In [53], a 25 m Vestas wind turbine blade was conducted full scale testing when subjected to a flapwise load in Risø National Laboratory. The objective of these tests is to learn about how a wind turbine blade fails when exposed to a large flapwise load and how failures propagate. The ultrasonic scan of the surface of the blade was used to full scale testing, and the experiment results show it is very useful for detection of defects, especially in the layer between the skin laminate and the load carrying main spar. And also acoustic emission was successfully used for the detection of damages in the blade during the full scale testing. The experiments contains measurements of the total deflection of the blade, the local deflection of the skin and the load carrying main spar and also measurement of strain all as a function of the applied load and up to failure of the blade.

In [54], two 16 m blades have been used to perform full scale testing by the acoustic emission (AE) monitoring in parallel with standard testing procedures. A comprehensive assessment of the application of AE monitoring complementing structural testing of composite material blades was conducted and respective methodologies were developed. Moreover, online analysis of AE data included damage location and criticality assessment by use of pattern recognition software previously calibrated through tests on small blades. The outcome of these experiments reveals that the critical areas can be effectively identified and assessed with respect to the blade's structural integrity, thus reducing the likelihood of untraceable damage.

In [27], a two-axis servo-hydraulic system has been implemented for full-scale fatigue testing of wind turbine blades at NREL. The details of experiments process have been described in Section 3.2. In short, two-axis testing has several advantages over single-axis testing including introducing a phase angle between flap and lead-lag moments, a varying resultant load angle. The drawback to two-axis testing is the considerable complexity compared with the single-axis setup. Hardware and software tools were developed to minimize the complications.

In [30], a small wind turbine blade which length is 2.5 m was also conduced full scale fatigue testing by means of a mechanically operated test rig. Furthermore, a crack started in a region of the blade where the highest stresses were predicted by the detailed finite element model of the blade. The predicted life of the blade from the life model [29,30] is in reasonable agreement with the experimental results.

In [55], the Risø National Laboratory for Sustainable Energy presents the setup and result of a full-scale testing of a reinforced glass fiber/epoxy box girder used in 34 m wind turbine blade. Various kinds of measuring equipment have been used during these tests: acoustic emission, 330 strain gauges, 24 mechanical displacement devices and two optical deformation measuring systems. The mechanical displacement devices measured both global (absolute) and local (relative) deflection and the optical systems measured surface deformation. The experimental investigation consisted of the following load configurations: flapwise bending and torsion.

In [15], a full-scale 34 m composite wind turbine blade was tested to failure under flapwise loading. In additional, the LM Wind Power's [56] have performed some full scale testing for wind turbine blades. The largest of full scale testing has recently been extended, with room for blades up to 80 m long. The facilities have been upgraded which involved installing one of the strongest cast concrete structures in the world—the anchor block. This is because the bending moment of the blade roots more than doubles in relation to the length of the blade.

It's clear that the cost of full-scale testing of wind turbine blade is considerably high. Practical and economic considerations have prevented testing conditions from representing load cases, and this is the main reason why there are not many publications available about the subject. Normally only one full-scale test is performed with each blade type and the tests are normally stopped before failure. Many full-scale testing methods of wind turbine blades have major combined with fatigue testing, static testing and modal testing. According to these literatures, fewer full-scale testing of big size blades have preformed which the blades length can over dozens of meters. In the future, larger testing places will be required, and more kinds of testing equipments should be developed which combined with different loading methods as wind turbine blades grows beyond 100 m. So full-scale testing has played a more and more important role for performance test.

5. Non-destructive testing/inspecting

Wind turbine blades are complicated objects for inspecting because they have an arbitrary curved surface, are multi-layered, have variable thickness and are made from anisotropic materials. The wind turbine blades consist of glass fiber reinforced plastics (GFRP) and sandwich areas containing wood or plastic foam. The blades are manufactured as two halves and glued together afterwards. Moreover, the blades need to service several decades. So, there is a growing need for testing/inspecting technologies that can reveal hidden flaws and defects in these materials. non-destructive testing (NDT) or non-destructive evaluation (NDE) is commonly used to monitor structures before, during, and after testing. In this section, different non-destructive testing/inspecting technologies based on ultrasound,

acoustic emission, thermograph, X-ray imaging and so on are surveyed.

5.1. Acoustic testing/inspecting

The composite materials used in wind turbine blade are all layered structures. Typical defects are delaminations, adhesive defects, resin-poor areas and so on. Ultrasonic non-destructive can reveal these flaws quickly, reliably and effectively and is the most often used non-destructive composite materials inspecting technology in industry. The propagation characteristics of ultrasonic waves are used to determine material properties throughout the volume of a turbine blade. This technique is especially useful for detecting surface and subsurface flaws.

In [57], the Sandia National Laboratories have developed an acousto-ultrasonic inspecting technique to evaluate the structural integrity of the epoxy bond interface between a metal insert and the fiber glass epoxy composite of wind turbine blade. The ultrasonic C-scan imaging can be used for the area mapping of the composite delamination or interface disbond. Comparison of the inspecting data with a destructive visual examination of the bond interface to determine the extent of the disbond showed good agreement between the acousto-ultrasonic inspecting data and the visual data. However, the influence of overlapped reflections, scattering and attenuation of the reflected ultrasonic waves from the multi-layered structure appears. The scattering effect also has a negative impact to the propagating ultrasonic waves and requires to use lower frequencies.

In [58], two NDT techniques which were acoustic emission and coherent optical have been used in Sandia National Laboratories. The former monitors the acoustic energy produced by the blade as it is loaded. The latter uses electronic shearography to measure the differences in surface displacements between two load states. The experiment results demonstrated that these two techniques are able to locate and monitor both high damage regions and flaws in the blade structure.

In [59], the ultrasonic air-coupled technique using guided waves has been used for inspecting of wind turbine blades in Ultrasound Institute, Kaunas University of Technology. Moreover, simulations of group and phase velocity dispersion curves as well as leakage losses versus frequency for defected and defect free regions were performed using the numerical global matrix model. The experiments show that the selected air-coupled ultrasonic technique, using Lamb waves, allows finding defects in wind turbine blades. The ultrasonically obtained images (A-scan, B-scan, C-scan) show defects geometry and approximate dimensions.

In [60], two different acoustic techniques which were used to damage detection of wind turbine blade have been researched. To detect missing or kissing bond areas from the outside of the blade the impulse-echo-technique is used. An ultrasonic pulse is sent into the material and is reflected at flaws or material boundaries. This pulse has to be strong because the GFRP are highly damping. It is difficult to see through several centimeters of GFRP and the choice of the ideal transducer is very important. To detect delaminations within the laminates of the turbine blade a local resonance spectroscopy is used. A small hammer is used to tap onto the blade and the excited sound is recorded using a microphone. A structural change within the material is displayed in a change of the frequency content. Furthermore, the exciting signal is recorded and gives additional information about the structural health of the wind turbine blade. To inspect bonding areas from outside the blade will be a great advance in wind turbine safety.

In [61], methodologies for applying AE non-destructive testing techniques during wind turbine blade certification tests were developed and demonstrated during a series of tests on a set of small blades. The applicability of a static proof test, using an AE examination loading, has been demonstrated. Blades passing this test can be expected to survive continuous loading at this level.

In [62], another ultrasonic technique, which could be suitable for testing of wind turbine blades, is based on exploitation of ultrasonic guided waves. Application of the ultrasonic guided waves allows estimation of location and type of the internal defects. In the case of guided wave's interaction with structural discontinuities, the guided waves scattering in all directions as well as mode conversion occurs. The different transducer techniques for generation and reception of guided waves, including both conventional and non-conventional piezoelectric transducers are proposed in [38].

In [63], ultrasonic contact pulse-echo immersion testing with moving water container has been selected for inspecting of wind turbine blade, because this type of the inspecting can be performed having access just from the one side of the wind turbine blade. The ultrasonic contact pulse-echo immersion testing technique with two types of ultrasonic transducers mounted into a moving water container was used for investigation of the artificial internal defects in a wind turbine blade. In the experiments, these defects (diameter 81 mm, 49 mm and 19 mm) were made on the internal side of the main spar. The performed measurements show that the contact pulse-echo immersion testing using the moving water container can help to identify the shape and the size of the internal defects better. The higher frequency focused transducer should be used in order to detect delamination type defects near the outer surface of the wind turbine blade. The low frequency planar transducer allows detecting delaminations and thickness variations in deeper layers. Furthermore, the best results (detection of different types of defects in different layers) are achieved combining different ultrasonic techniques.

In [64], two non-destructive testing techniques using ultrasonic and sonic were collaborated to detect and localize damages within the turbine blades. The ultrasound-echo technique is suitable to detect flaws within the bonding areas beneath several centimeters of GFRP. The technique can be used with a dry coupling of ultrasonic transducers. The local resonance spectroscopy is an advancement of the manual tapping tests. A sound is excited by a hammer impulse on the surface. The excited sound is recorded using a microphone. Additionally the force signal of the excitation is recorded and gives additional information. Using this technique near surface damages can be detected very simple by interpreting the force signals recorded at the hammer. The sound signals can be used to visualize the inner structure of a wind turbine blade. Both techniques are able to help to make wind energy safer and reduce failures of wind energy plants.

5.2. Infrared thermography and X-ray imaging

Infrared thermography can detect variations in the thermodynamic properties of the object then produce surface temperature patterns. Hot spots, due to degeneration of components or bad internal contact can be identified in a simple and fast manner. Moreover, it is used to examine the blade throughout its length, measuring exactly the same points each time. It records temperature differences in the adhesive, possibly identifying flaws, and takes a series of pictures. X-ray imaging relies on the different levels of absorption of X-ray photons as they pass through a material. The X-ray measurement data contains quantitative information about variations in density, which is caused by changes in material properties or internal delaminations.

In [65], experimental evaluation of the stress distribution based on the thermal stress analysis has been performed on a wind turbine blade at the second modal vibration regime. The experiment is designed that small wind turbine blade was exposed to a simple oscillating movement, similar to the real

movement when the blade is mounted on a wind turbine rotor. And internal loads of the blade structure, caused by deflections during oscillated movement, provide energy dissipation in their internal material structure. Energy dissipation, due to the elastic stresses in the structure, can be detected with an infrared thermal imaging camera. Furthermore, the finite element modal frequency analysis of the 3D scanned model has been used to evaluate the global structural behavior and approve thermal stress analysis results.

In [66], as a NDE tool, digital infrared thermography camera was explored in two separate wind turbine blade fatigue tests. The first test was a fatigue test of part of a 13.1 m wood-epoxy-composite blade. The second test was on a 4.25 m pultruded fiber glass blade section driven at several mechanical resonant frequencies. The digital infrared camera can produce images of either the static temperature distribution on the surface of the specimen, or the dynamic temperature distribution that is in phase with a specific frequency on a vibrating specimen. The dynamic temperature distribution (due to thermoplastic effects) gives a measure of the sum of the principal stresses at each point on the surface. In the wood-epoxy-composite blade fatigue test, the point of ultimate failure was detected long before failure occurred. The mode shapes obtained with the digital infrared camera, from the resonant blade tests, were in very good agreement with the finite-element calculations. In addition, the static temperature images of the resonating blade showed two areas that contained cracks. Close-up dynamic infrared structure that analysis images of these areas showed the crack agreed with subsequent dye-penetrant analysis.

In [67], as one of the several diagnostic techniques, infrared thermography non-destructive testing was used in full-scale wind turbine blades fatigue test at the National Wind Technology Center at NREL and Sandia National Laboratories. In this experiment, a cyclic load is applied to the wind turbine blade until the blade fails. At the start of a fatigue testing, the entire structure is close to the laboratory ambient temperature, but as the number of fatigue cycles increases, friction generated between the various components inside the blade generates thermal energy. This thermal energy conducts to the surface and can be sensed by an IR thermography camera. In the IR image, warm areas are light-colored and cooler areas are dark-colored. The thermal information helps test technicians and design engineers locate areas experiencing high strains; the pattern or signature can often appear well before the blade fails.

In [68], the principle technique of passive and active thermography using for the inspecting of wind turbine blades were introduced in this article. Six testing examples show passive and active thermography is a powerful technique for the detection of different defects like delaminations, air bubbles, dry glass fiber reinforced and structural faults. Three examples of passive thermography inspectings and three examples of active thermography inspectings have been researched which were used in three different stages. These examples show the possibility to detect defects like poor bonding, delaminations and internal structural faults by using passive techniques. But more advanced techniques like active online thermography will demonstrate the outstanding results in finding even small defects in these up to 65 m long rotor blades of wind turbines.

In [69], the application of AE monitoring and thermoelastic stress analysis during full-scale static and fatigue tests on wind turbine blades have been developed. A novel thermoelastic stress analysis technique has been developed which identified all damaged areas in a test blade and for which the signal magnitude appeared proportional to damage severity. The techniques work independently of each other. Thermoelastic stress analysis can be used to verify the overall stress distribution at the blade surface as well as to detect developing damage. Acoustic emission monitoring specifically detects damage, but requires a large sensor array due to signal attenuation in the blade material.

In [70], real time X-ray inspecting (known as radioscopy) has been accomplished using a microfocus X-ray source combined with an X-ray image intensifier tube in wind turbine blade damage inspecting. In this project, the propagation of the damage was determined by use of ultrasonic and X-ray surveillance during stops in the test-series.

As it is known, wind turbine blades are fabricated with composite materials with polymeric matrices and the current manufacturing processes are still highly manual resulting in different types of defects. NDT techniques can provide surface and internal information of the blade. But, different NDT techniques can show different material properties and different defects. In this paper, the detection capabilities and performance of ultrasonic, shearography, thermography and X-ray CT techniques have been investigated. Up to now, ultrasonic NDT techniques are used more widely than others. And thermography has shown to be a potential technique for wind turbine blade inspection. The main advantage is relatively low inspection time, low cost, and highly sensible to delaminations. X-ray CT has clear potential for NDT inspection of composite materials. So, I think that the desirable inspecting results can be obtained by integrating several different non-destructive testing technologies [71].

6. Structural health monitoring (SHM)/condition monitoring (CM)

The trend in blade design is toward complex blade shapes and increasing in size. Blade geometry and materials are becoming high-tech and complex. If any blade fails, the rotor can become unbalanced which can destroy the entire wind turbine. Therefore, it is important to acquire an early indication of structural or mechanical problems allows operators to better plan for maintenance, possibly operate the machine in a de-rated condition rather than take the turbine off-line, or in the case of an emergency, shut the machine down to avoid further damage. In other word, the SHM/CM system will benefit the wind turbine blades including early damage warning, preventive/predictive maintenance which reduced need for service inspecting, reduced component failure, and reduced average failure cost, reduced downtime and optimized wind energy service management. SHM/CM technologies of wind turbine blades will be surveyed as follows.

Risø National Laboratory has performed a big project "Fundamentals for Remote Structural Health Monitoring of Wind Turbine blades-A Preproject" [72]. So far, it is the most integrated research for SHM of wind turbine blades, which included six parts. The preproject concerns the use of sensors in large off-shore wind turbine blade for monitoring of structural health. A long-term goal is to develop an approach for detection of damage and estimate the severeness of damage on the residual life of wind turbine blade. Through this research, three key technical questions for SHM of wind turbine blades have been answered: (1) which sensors can have potential for the detection of damages in wind turbine blade; (2) can the sensors locate the damage site? (3) How many sensors must be used for surveillance of a large wind turbine blade (how closely spaced should sensors be?)?

The NASA Kennedy Space Center SHM System of wind turbine blades was described. Zayas et al. [73] implemented a wave propagation based SHM system by instrumenting the high-pressure side of the blade with a macro-fiber composite (MFC) actuator and three MFC sensors, and on the low-pressure side an MFC actuator and two MFC sensors. His setup was an incremental

enhancement, with the application of the electronic filter, to the setup on previous wind turbine blade testing. The actuator/sensors needed to encompass the expected failure area. As in the previous blade tests, NASA provided all the SHM equipment except the data acquisition system[74]. After the initial system checkout, NREL testing staff exercised the NASA SHM system, acquired the data, and posted the data on a secure NREL FTP file server to allow remote file access by the testing partner.

In [75], the Virginia Tech (VT) SHM system of wind turbine blade was introduced. The technique utilizes small piezoceramic (PZT) patches attached to a structure as self-sensing actuators to both excite the structure with high-frequency excitations, and monitor any changes in structural mechanical impedance. By monitoring the electrical impedance of the PZT, assessments can be made about the integrity of the mechanical structure. The tests on the CX-100 WTB using the impedance method were successful enough to continue to pursue testing the method on the TX-100 fatigue test. Unfortunately, during the fatigue test, the impedance method was found to not be sensitive to structural changes in the blade. Macro-fiber composite sensors were used as self-sensing actuators and had to be placed on the outside of the pre-manufactured blade. These factors along with the blade being larger than the previously tested section and not having any boundaries near the sensors possibly contributed to insensitivity. In conclusion, the impedance-based SHM is a method which has shown promise on a wide variety of structures. However, the method seems to be insensitive to damage and therefore the impedance method is not currently feasible for SHM of wind turbine blade.

In [76], four vibration-based techniques, which were used in a SHM system, are tested for detecting damage on fiberglass wind turbine blades. These are the transmittance function, resonant comparison, operational detection shape, and wave propagation methods. The methods are all based on measuring the vibration response of the blade when it is excited using piezoceramic actuator patches bonded to the blade. The vibration response of the blade is measured using either piezoceramic sensor patches bonded to the blade, or a scanning laser doppler vibrometer (SLDV). These experiments indicate the feasibility of using piezoceramic patches for excitation and a SLDV or piezoceramic patches to measure vibration to detect damage.

In [77], a structural neural system (SNS) for SHM of wind turbine blades was developed which collaborated between the Intelligent Mechanisms Laboratory at North Carolina A&T State University and the Smart Materials Nanotechnology Laboratory at the University of Cincinnati. The NREL sponsored the work and engineers from Sandia National Laboratories provided guidance. The SNS is based on Vibration, AE, and strains monitoring, which is a practical approach for low-cost SHM of large composite structures such as wind turbine blades. The main advantage of the SNS is that many sensor elements can be used with only 2–4 channels of data acquisition. And this tremendously simplifies SHM. Furthermore, the method is passive, which means no pre-damage data or diagnostic waveforms are needed. Finally, the SNS was tested to identify damage initiation and propagation on a 9-m wind turbine blade. The development of a smart blade that uses continuous sensors and microelectronics to mimic the biological nervous system is the eventual goal of the research.

In [78], SHM research is being performed by North Carolina A&T (NCA&T), the NREL and Sandia Laboratories to develop a smart blade. A smart blade has an embedded sensor system integrated into the blade by the blade manufacturer. This sensor system will continuously monitor the condition of the blade, warn of initiating damage, and provide instant information that can be used to regulate the loading in the blade and reduce or prevent fatigue damage of the blade.

In [79], the authors describe how AE can be used for SHM system of wind turbine blade. Two different AE systems are described. It is showed how both the position of damage and the development and the criticality of damage can be determined from AE data. Moreover, the future prospect for CM system is discussed. The author considered optical fiber is another sensor technology which seems very promising.

In additional, many researchers have developed the SHM system and CM system of wind turbine such as gearbox, tower. In [80], the focus is on CM systems and its application of wind turbines gearbox, one of the most critical components in terms of high failure rates and long mean down time. In this paper, the CM system is used to maintenance optimization for wind turbines. In [81], wireless sensor technologies are deployed on two wind turbine structures to provide better models of wind turbine dynamic behavior and response to loading. Gearbox fault is widely received as the leading issue for wind turbine drive train condition monitoring among all subsystems [82–83]. In [84], an advanced CM system has been implemented. In this CM system, a variety of different sensors were used for wind turbine components, a proper supervisory control and data acquisition system (SCADA) was integrated. Analyzing sensor data, implementing fault detection algorithms and using advanced signal processing will result in an improved prediction of the possible malfunctions that may occur.

7. New trend of testing, inspecting and monitoring technologies

As the size of blades has significantly grown and the surface curve of blade structure has became more complexity over the past decade, there is a dramatically need to testing, inspecting and monitoring for wind turbine blade during manufacture, install, and service stage. In order to guaranty the service safety and extend the span life of wind turbine blade, new testing, inspecting and monitoring technologies and methods emerged endlessly due to the development of physics, compute, network, automation and mechanics. In sum, the trend of testing, inspecting and monitoring technologies are as follows:

(1) Full scale testing will become the most important method for validating the comprehensive performance of wind turbine blades. More and more blades certification will require full scale testing in the future. Furthermore, the static testing, fatigue testing and modal testing will be performed using full scale blade in order to obtain better testing results. However, it is very difficult to perform full scale testing, especially for the huge blade which the length of blade exceeds 100 m or even. How to perform the complexity loads in different point on a wind turbine blade, and how to exert environment affect (for example fog chamber) on the subcomponents of full scale testing, how to develop sensitivity sensors to sense the damage signal. Only all these problems should be resolved, the full-scale testing of wind turbine blades will be carried out perfectly.

(2) Structural health monitoring which has characteristics of real-time, remote, wireless and smart will play more and more important role. Future research work of SHM should focus in three new directions. Firstly, wireless sensor networks (ad hoc and mesh) will be widely used in SHM system of wind turbine blades in the future because of flexible network architecture, convenient install and deployment, lower cost and so on. Secondly, fiber optic sensors, because of their small volume, should be embedded into the blades which can be called “smart blades”. Thirdly, damage detection algorithms must be included

in the computing cores of the SHM system to provide automated monitoring and diagnosis of the service condition of wind turbine blade.

(3) Non-contact and remote non-destructive testing/inspecting technologies will become priority research areas. The blade is too large so that it is difficult to transport the in-service blade which has some problems to the laboratory for diversity non-destructive testing. So, non-contact and remote non-destructive testing has overwhelming advantages in online testing and inspecting. In addition, many literatures have proved that acoustic testing methods, especially acoustic emission and ultrasonic, will become the most potential technology for online or offline non-destructive testing of wind turbine blades. But the acoustic signal process methods will encounter formidable challenges for identifying the various damage patterns of blades. Furthermore, combined with different non-destructive testing will benefit to find different types of defects in different places of wind turbine blade. But the acquired data from different NDT which has characteristics of different dimension, heterogeneous will very difficultly to be efficiently fused for damage identification, such as acoustic signal data and IR signal data. Therefore, selected fitting NDT technology and damage data fusion methods will become future research work.

(4) Combined numerical simulation analysis with testing, inspecting and monitoring technologies are also major research content in the future. The finite element method has traditionally been used in the development of wind turbine blade mainly to investigate the global behavior in terms of, for example, eigenfrequencies, tip deflections, and global stress/strain levels. How to build more precisely 3D FE model and how to predict the local deformations and stresses are the two key problems. How to utilize the testing, inspecting and monitoring data to calibrate the FE model is another key technology. A big advantage of using FEM is that, once the model is setup and calibrated, complex load cases representing actual wind conditions can be analyzed. Moreover, it will remarkable reduce the cost of testing, inspecting and monitoring for wind turbine blade.

(5) The testing, inspecting and monitoring standards of wind turbine blades are considered to relatively lack. Making standards will become very exigent and important research work in the future, especially full scale testing and NDT of wind turbine blades. Now, blade certification can be done to a degree under the International Electrotechnical Commission (IEC)-CAP standard. However, the CAP standard is not sufficient as it stands. There are some troubles to make standards. On the one hand, the standards should reach an agreement among designer, developer, manufacturer, installer and maintainer in different countries. On the other hand, how to make the testing and inspecting procedures is another problem. The standards should regulate testing and inspecting including the reasonable loads, testing/inspecting conditions and so on.

8. Conclusions

In this paper, a survey of testing, inspecting and monitoring techniques for wind turbine blade is presented. And static testing, fatigue testing, modal testing, full scale testing, non-destructive testing, structural health monitoring or condition monitoring of wind turbine blades have been analyzed in detail. The analysis of the different technologies had shown that each technology has its application areas. Different techniques can show different material properties and different defects. Finally, the development trends in the future have been also described and some suggests have been given.

Acknowledgments

This work was supported by Project supported by National Natural Science Foundation of China (Grant No. 51005014).

References

[1] Herbert GMJ, Iniyanb S, Sreevalsanc E, Rajapandian S. A review of wind energy technologies. Renewable and Sustainable Energy Reviews 2007;11(6):1117–45.
[2] Blanco MI. The economics of wind energy. Renewable and Sustainable Energy Reviews 2009;13(6-7):1372–82.
[3] Chris R. Wind turbine blades: big and getting bigger. Composites Technology 2008.
[4] Raišutis R, Jasiūnienė E, Šliteris R, Vladišauskas A. The review of non-destructive testing techniques suitable for inspecting of the wind turbine blades. Ultragarsas 2008;63(1):26–30.
[5] 〈http://www.metaefficient.com/news/new-record-worlds-largest-wind-turbine-7-megawatts.html〉.
[6] Thomsen OT. Wind turbine blades–design and performance. Energy Group Newsletter 2009;31:3–6.
[7] Thomsen OT. Sandwich materials for wind turbine blades-present and future. Journal of Sandwich Structures and Materials 2009;11(7):7–26.
[8] John FM, Daniel DS, Pancasatya A. Composite materials fatigue issues in wind turbine blade construction. Los Angeles, CA: SAMPE; 2008.
[9] Malhotra P, Hyers RW, Manwell JF, McGowan JG. A review and design study of blade testing systems for utility-scale wind turbines. Renewable and Sustainable Energy Reviews 2012;16:284–92.
[10] Kim SW, Kim EH, Rim MS, Shrestha P, Lee I. Structural Performance tests of down scaled composite wind turbine blade using embedded fiber bragg grating sensors. International Journal of Aeronautical & Space Science 2011;12(4):346–53.
[11] Yang JS, Peng CY, Xiao JY, Zeng JC, Xing SL, Jin JT, et al. Structural investigation of composite wind turbine blade considering structural collapse in full-scale static tests. Composite Structures 2013;97:15–29.
[12] Larwood, S, Musia, W. Comprehensive testing of Nedwind 12-meter wind turbine blades at NREL. In: The 19th American society of mechanical engineers (ASME) wind energy symposium, Reno, NV, 2000, NREL/CP-500-27497.
[13] Paquette J, van Dam J, Hughes S. Structural testing of 9 m carbon fiber wind turbine research blades. AIAA 2007 Wind Energy Symposium Reno 2007.
[14] Branner. K. Static testing of cross-section of wind turbine blade. In: the 3rd International conference on composites testing and model identification. Portugal: Universidade do Porto; 2006 10–12 April.
[15] Jensen FM, Falzon BG, Ankersen J, Stang H. Structural testing and numerical simulation of a 34 m composite wind turbine blade. Composite Structures 2006;76(1-2):52–61.
[16] Berring, P, Branner, K, Berggreen, C, Knudsen, HW. Torsional performance of wind turbine blades—part I: experimental investigation. In: The 16th international congress on composite materials, Kyoto, Japan, 2007.
[17] Overgaard LCT, Lund E, Thomsen OT. Structural collapse of a wind turbine blade. Part A: static test and equivalent single layered models. Composites Part A: Applied Science and Manufacturing 2010;41(2):257–70.
[18] Samborsky DD, Sears AT, Mandell JF, Kils O. Static and fatigue testing of thick adhesive joints for wind turbine blades. ASME Wind Energy Symposium 2009 AIAA-2009-1550.
[19] 〈http://www.mts.com/ucm/groups/public/documents/library/dev_005130.pdf〉.
[20] Malhotra P, Hyers RW, Manwell JF, McGowan JG. A review and design study of blade testing systems for utility-scale wind turbines. Renewable and Sustainable Energy Reviews 2012;16:284–92.
[21] Greaves PR, Dominy RG, Ingram GL, Long H, Court R. Evaluation of dual-axis fatigue testing of large wind turbine blades. In: Proceedings of the institution of mechanical engineers. Part C: Journal of Mechanical Engineering Science 2012;226:1693–704.
[22] Lai FM, Yang SH, Wu JH, Hsueh CT, Yang CC, Wang BH, et al. Development of fatigue test system for small composite wind turbine blades. Procedia Engineering 2011;14:2003–13.
[23] Farinholt KM, Taylor SG, Park G, Ammerman CM. Full-scale fatigue tests of CX-100 wind turbine blades. Part I: testing. SPIE 2012.
[24] Taylor SG, Jeong H, Jang JK, Park G, Farinholt KM, Todd MD, et al. Full-scale fatigue tests of CX-100 wind turbine blades. Part II: analysis. SPIE 2012.
[25] Wei J, McCarty J. Acoustic emission evaluation of composite wind turbine blades during fatigue testing. Wind Engineering 1993;17(6):266–74.
[26] Mark, AR, Joshua, P, Jonathan, RW, Rudolph, JW Experimental results of structural health monitoring of wind turbine blades. In: 46th AIAA aerospace sciences meeting and exhibit, Reno, NV, 2008.

[27] Hughes, SD, Musial, WD, Stensland, T. Implementation of two-axis servo-hydraulic system for full-scale fatigue testing of wind turbine blades. In: Proceedings of windpower 99, Burlington VT, June 1999.
[28] White, D, Musial, W, Engberg, S. Evaluation of the B-REX Fatigue testing system for multi-megawatt wind turbine blades. In: the 43rd AIAA aerospace sciences meeting and exhibit Reno, Nevada, 2005.
[29] White D. New method for dual-axis fatigue testing of large wind turbine blades using resonance excitation and spectral loading. University of Colorado-Boulder; 2003 October.
[30] AE Jayantha, DC Philip. Accelerated full scale fatigue testing of a small composite wind turbine blade using a mechanically operated test rig. SIF 2004 Structural Integrity and Fracture, Brisbane, Australia, 2004.
[31] Beattie, AG. Acoustic emission monitoring of a wind turbine blade during a fatigue test. In: The 35th AIAA aerospace sciences meeting and asme wind energy symposium, Reno, Nevada,1997.
[32] White, JR, Adams, DE, Rumsey, MA Modal analysis of CX-100 rotor blade and micon 65/13 wind turbine. In: Conference proceedings of the society for experimental mechanics series vol. 10, 2011, p. 15–27.
[33] Deines K, Marinone T, Schultz R, Farinholt K, Park G. Modal analysis and SHM investigation of CX-100 wind turbine blade. In: Conference proceedings of the society for experimental mechanics series vol. 8, 2011, p. 413–438.
[34] Kusnick, JF, Adams, DE. Vertical axis wind turbine operational modal analysis in sheared wind flow. In: Conference proceedings of the society for experimental mechanics series vol. 27, 2012, p. 333–344.
[35] Tenguria N, Mittal ND, Ahmed. S. Modal analysis for blade of horizontal axis wind turbine. Asian Journal of Scientific Research 2011;4(4):326–34.
[36] Tartibu LK, Kilfoil M, Merwe. AJVD. Modal testing of a simplified wind turbine blade. International Journal of Advances in Engineering & Technology 2012;4(1):649–60.
[37] Tarfaoui M, Khadimallah H, Imad A, Pradillon JY. Design and finite element modal analysis of 48 m composite wind turbine blade. Applied Mechanics and Materials 2011;146:170–84.
[38] Paulsen, U.S., Schmidt, T., O Erne. Developments in large wind turbine modal analysis using point tracking videogrammetry. In: Conference proceedings of the society for experimental mechanics series, 2011, 10: 187–198.
[39] Tcherniak, D., Chauhan, S., Hansen, M.H.. Applicability limits of operational modal analysis to operational wind turbines. In: Conference proceedings of the society for experimental mechanics series, 2011, 10: 317–327.
[40] Yin JC, Liu W, Chen P. Modal re-analysis of rotary wind turbine blades in refinement design. Wind Energy 2012;15(6):864–81.
[41] Surendra NG, Yang J, Richardson M. Using Modal analysis for detecting cracks in wind turbine blades. Sound & Vibration 2011:10–3.
[42] Zhu SF, Rustamov I. Structural design and finite element analysis of composite wind turbine blade. Key Engineering Materials 2012;525:225–8.
[43] Ozbek M, Rixen DJ. Operational modal analysis of a 2.5 MW wind turbine using optical measurement techniques and strain gauges. Wind Energy 2012. http://dx.doi.org/10.1002/we.1493.
[44] Larsen GC, Morten HH, Andreas B, ngemar CI. Modal analysis of wind turbine blades. Risø–R–1181 (EN). Roskilde: Risø National Laboratory; 2002.
[45] Pedersen HB, Kristensen OJD. Applied modal analysis of wind turbine blades. Risø–R–1388 (EN). Roskilde: Risø National Laboratory; 2003.
[46] NLREG Nonlinear Regression Analysis Program ver. 4.1, Sherrod Software, Brentwood, Tennessee.
[47] Mao, HJ Full-scale testing and structural analysis of wind turbine blades. Master thesis, Beijing: Chinese Academy of Science.
[48] IEC 61400-1. Wind turbines – Part 1: design requirements. 3rd ed. 2005.
[49] IEC 61400-22. IEC TS 61400-22 Ed.1: Wind turbines – Part 22: Conformity testing and certification of wind turbines, 2008.
[50] IEC 61400-23. Wind turbine generator systems – Part 23: full-scale structural testing of rotor blades, 2001.
[51] National Renewable Energy Laboratory (NREL). NREL wind turbine blade. Structural testing of the modular. Wind energy MW45 Blade. Cooperative research and development. Technical Report, DE-AC36-08GO28308, 2012.
[52] Yang JS, Peng CY, Xiao JY, Zeng JC, Yuan Y. Application of videometric technique to deformation measurement for large-scale composite wind turbine blade. Applied Energy 2012;98:292–300.
[53] Jørgensen ER, Borum KK, McGugan MG, Thomsen CL, Jensen FM, Sørensen CP. Full scale testing of wind turbine blade to failure-flapwise loading. Risø-R-1392(EN). Roskilde: Risø National Laboratory; 2004.
[54] Lekou DJ, Vionis P, Joosse PA, van Delft DRV, Kouroussis D, Anastasopoulos A, et al. Full-scale blade testing enhanced by acoustic emission monitoring. european wind energy conference, EWEC2003, Madrid, Spain, 2003.
[55] Jensen FM, Branner K, Nielsen PH, Berring P, Antvorskov TS, Nielsen M, et al. Full scale test of a SSP 34 m box girder 1. Data report. Risø-R-1622(EN), Risø National laboratory for sustainable energy. Roskilde, Denmark: Technical University of Denmark; 2008.
[56] 〈http://www.lmwindpower.com/Blades/Technology/Test/Fullscale〉 test.aspx.
[57] Gieske JH, Rumsey MA. Nondestructive evaluation (NDE) of composite/metal bond interface of a wind turbine blade using an acousto-ultrasonic technique. ASME Wind Energy Symposium 1997:249–54.
[58] Sutherland H, Beattie A, Hansche B, Musial W, Allread J, Johnson J, et al. The application of non-destructive techniques to the testing of a wind turbine blade. Report SAND93-1380, Sandia National Laboratory.
[59] Raišutis R, Jasiūnienė E, Žukauskas E. Ultrasonic NDT of wind turbine blades using guided waves. Ultragarsas 2008;63(1):7–11.
[60] JÜNGERT, A. Damage detection in wind turbine blades using two different acoustic techniques. In: The 7th fib PhD Symposium in Stuttgart, Germany, 2008.
[61] Joosse PA, Blanch MJ, Dutton AG, Kouroussis DA, Philippidis TP, Vionis PS. Acoustic emission monitoring of small wind turbine blades. Journal of Solar Energy Engineering 2002;124:446–54.
[62] Raghavan A, Carlos E, Cesnik S. Review of guided-wave structural health monitoring. The Shock and Vibration Digest 2007;39:91–114.
[63] Jasiūnienė E, Raišutis R, Šliteris R, Voleišis A, Jakas M. Ultrasonic NDT of wind turbine blades using contact pulse-echo immersion testing with moving water container. Ultragarsas 2008;63(3):28–32.
[64] JUENGERT A, GROSSE CU. Inspection techniques for wind turbine blades using ultrasound and sound waves. Nantes, France: Non-Destructive Testing in Civil Engineering; 2009 June 30th.
[65] Krstulović-Opara L, Klarin1 B, Domazet. Ž. A non-destructive wind turbine blade analysis based on the thermal stress analysis. international symposium on coupled methods in numerical dynamicsSplit. Hrvatska 2009:255–65.
[66] Beattie AG, Rumsey. M. Non-destructive evaluation of wind turbine blades using an infrared camera. Reno, NV: ASME 18th Wind Energy Symposium; 1999.
[67] Rumsey MA, Musial W. Application of infrared thermography non-destructive testing during wind turbine blade tests. Journal of Solar Energy Engineering 2001;123:271.
[68] Meinlschmidt, P, Aderhold, J Thermographic inspection of rotor blades. In: 9th European conference on NDT, Berlin, 2006.
[69] Dutton AG. Thermoelastic stress measurement and acoustic emission monitoring in wind turbine blade testing. London: European Wind Energy Conference; 2004.
[70] Kristensen OJD, McGugan M, Sendrup P, Rheinländer J, Rusborg J, Hansen AM, et al. Full-scale test of wind turbine blade, using sensors and NDT. Risø-R-1333(EN). Roskilde, Denmark: Risø National Laboratory; 2002.
[71] Amenabar I, Mendikute A, López-Arraiza A, Lizaranzu M, Aurrekoetxea J. Comparison and analysis of non-destructive testing techniques suitable for delamination inspection in wind turbine blades. Composites: Part B 2011;42:1298–305.
[72] Bent FS, Lading L, Sendrup P, McGugan M. Fundamentals for remote structural health monitoring of wind turbine blades—a Preproject. Risø-R-1336(EN). Roskilde, Denmark: Risø National Laboratory; 2002.
[73] Zayas JR, Paquette J, Werlink RJ. Evaluation of NASA PZT sensor/actuator for structural health monitoring of a wind turbine blade. In: The 45th AIAA aerospace sciences meeting and Exhibit, Reno, NV, 2007.
[74] Berg, DE, Rumsey, MA, Zayas, JR. Hardware and software developments for the accurate time-linked data acquisition system. In: 2000 ASME Wind Energy Symposium, 2000.
[75] Pitchford, CW Impedance-based structural health monitoring of wind turbine blades. Master's thesis, Virginia Polytechnic Institute and State University, 2007.
[76] Ghoshal A, Sundaresan MJ, Schulz MJ, Pai PF. Structural health monitoring techniques for wind turbine blades. Journal of Wind Engineering and Industrial Aerodynamics 2000;85(3):309–24.
[77] Schulz MJ, Sundaresan. MJ. Smart sensor system for structural condition monitoring of wind turbines. Subcontract report, NREL/SR-500-40089. National Renewable Energy Laboratory 2006.
[78] Sundaresan MJ, Schulz MJ, Ghoshal A. Structural health monitoring static test of a wind turbine blade. Subcontract report, NREL/SR-500-28719. National Renewable Energy Laboratory 2002.
[79] Borum KK, McGugan M, Brøndsted P. Condition monitoring of wind turbine blades.The 27th Risø International Symposium on Materials Science. Roskilde, Denmark: Risø National Laboratory; 2006.
[80] Lucente M. Condition monitoring system in wind turbine gearbox. Master thesis, Royal Institute of Technology, Stockholm, Sweden, 2008.
[81] Swartz RA, Lynch JP, Sweetman B, Sweetman B, Rolfes R. Structural monitoring of wind turbines using wireless sensor networks. The ESF-NSF Workshop on Sensor networks for Civil Infrastructure Systems, Cambridge 2008.
[82] Lu B, Li YY, Wu X, Yang. ZZ. A Review of recent advances in wind turbine condition monitoring and fault diagnosis. Power Electronics and Machines in Wind Applications, Lincoln, NE 2009.
[83] Hameed Z, Hong YS, Cho YM, Ahn SH, Song CK. Condition monitoring and fault detection of wind turbines and related algorithms: a review. Renewable and Sustainable Energy Reviews 2009;13(1):1–39.
[84] Entezami, M Wind turbine condition monitoring system. PhD progress report, University of Birmingham, 2010.